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COLLISIONLESS EFFECTS ON THE SPECTRUM OF SECONDARY AURORAL ELEC--ETC(U)

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Collisionless Effects on the Spectrum of Secondary Auroral Electrons at Low Altitudes

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It is shown by use of particle computer simulations that collisionless interactions, due to energetic electron precipitation in the auroral zones, can be responsible for the break from the E-3 dependence of the secondary electron spectrum expected on the basis of collisional models, even at very low altitudes (< 180 km).

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CONTENTS

COLLISIONLESS EFFECTS ON THE SPECTRUM OF SECONDARY AURORAL ELECTRONS AT LOW ALTITUDES

Introduction

The differential flux of primary and secondary electrons under auroral activity has been the subject of a series of experimental measurements [Feldman et al. 1971; Arnoldy and Choy 1973; Reasoner and Chappel 1973; Feldman and Doering 1974; Matthews et al 1976]. A common feature of all these rocket experiments is that between 30-85 eV, where the measurements overlap in energy, the electron flux data can be fit by a power law $E^{-\alpha}$ with $.5 \le \alpha \le 1.0$. Theoretical models based on ionizing collisions of the primary (2-30 kev) electrons producing secondary and backscattered electrons, predict much steeper ($\sim E^{-3}$) and strongly altitude dependent spectra in sharp contrast with the observations [Banks et al 1974; Berger et al 1974; Rees and Maeda 1973]. It should be noted that the above models are in reasonable agreement with observed fluxes for energies below 20 eV (Fig.1).

In an earlier paper Papadopoulos and Coffey (1974a) demonstrated that collisionless processes can be very important in the auroral arcs and could explain the characteristic features of the secondaries observed by Reasoner and Chappel [1973] at altitudes 600-700 km. More recently Matthews et al [1976] demonstrated that similar processes can operate under intense auroral conditions down to altitudes of 130 km, and could account for several of their experimental observations. The fundamental physical idea of the Papadopoulos-Coffey theory was that the primary electron spectrum has the form of a large flux spike,

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which can thus be unstable and produce plasma waves with phase velocities near the velocity of the precipitating particles. When these waves reach a certain amplitude they become themselves unstable to parametric instabilities and decay to plasma waves of low phase velocity which can interact with the ambient plasma and create fast (> 20 ev) upstreaming and downstreaming secondary electron fluxes. An additional effect of the above process is the excitation of low frequency ion density fluctuations which can produce anomalous resistivity in the auroras [Papadopoulos and Coffey 1974b]. Detailed accounts of the theory can be found in the forementioned papers as well as in Papadopoulos [1975] and Papadopoulos et al [1974]. The derivations presented in the above papers are totally analytic and therefore several approximations were employed. In view of the importance of the problem in the understanding of the auroral processes, we decided to test some aspects of the formation of secondaries by using particle computer simulation techniques, which allow us to solve the complete non-linear problem, and compare the results with the experimental observations of Feldman and Doering [1975]. The complete simulation of the problem should include the collisional processes via a Fokker-Planck collision integral that computes energy deposition rates in a similar fashion as in Banks et al [1974] or Walt et al [1969] and the wave-particle interactions. In view of the large disparity in the time scales of these processes, the only reasonable way of producing such a program is by describing the wave-particle interactions by a diffusion tensor in velocity space whose properties have been determined by simulation studies of the collisionless microphysics. We are presently developing such a capability and the present study represents a step in this direction.

In this paper we assume that the spectrum of the secondary electrons is of the form E^{-3} (actually $E^{-3.2}$ to simulate the Feldman-Doering results) as expected from the collisional theory and examine the modifications that will be introduced due to the wave-particle interactions.

The present study starts with two basic assumptions:

(a) A secondary flux of the form $E^{-3.2}$ has been established by collisional processes.

(b) Electron plasma waves with phase velocities near the velocity of the primary spike like electron spectrum can be generated. Generation of such waves is a basic concept in plasma physics due to the interaction of precipitating beams with the plasma. Such waves have been recently observed in the aurora at altitudes of 180 km and with a modulation amplitude 5% [Spiger et al 1975].

Using particle simulations, where 10^4 particles are followed in their self consistent orbits and where the above assumptions are used as inputs at the initial time, we try to answer the following questions:

(i) Does the presence of the plasma waves, which are non-resonant with ambient particles, change the observed flux power law?

(ii) At what energies the break occurs?

(iii) Is this energy a function of the wave energy level?

(iv) What is the final high frequency and low frequency wave energy spectrum?

In order to keep as close as possible with the experimental data we carried our simulation for the parameters of the experiment of Feldman and Doering [1975], however the results have a much broader applicability.

In the next section we describe briefly the numerical code used for the studies. In Section III we present the results. In the final section we discuss the constraints, conclusions and the implications of the study.

II. Description of the Code

The simulations were done with a one-dimensional pure electrostatic hybrid code. The electrons are treated as discrete particles, the ions as a fluid. For this problem, the ion dynamics can be accurately described by the fluid equations [DuBois and Goldman 1967]. By using such a representation for the ions, we reduced the statistical noise in the ion background due to the finite number of simulation particles. By reducing the statistical fluctuation level, we were able to simulate much weaker instabilities then would have been possible with a pure particle simulation. Since we are interested in wave-particle interaction involving the electrons, we kept a particle representation of the electrons. The particle side of the code is based upon PPOWER [Boris, et al. 1973] and is typical of particle simulation codes presently in use. The particles are advanced using the internally (via Poisson's eq.) calculated electric fields. The fluid quantities-density, momentum and energy are advanced in time. A new electric field is then calculated from the sum of the fluid and particle charge density and the process is repeated. The fluid algorithm used in the minimum diffusion SHASTAX [Book et al. 1975].

III. Simulation Results

The initial configuration consists of a Maxwellian electron plasma with thermal velocity V_e, an initial symmetric secondary electron flux which starts at $|v_{min}| = 3V_e$ and decreases as $E^{-3.2}$ till $|v_{max}| = 6V_e$ with a total of 2.2% of the total number of electrons. The ions are treated as a fluid with a temperature equal to the electrons. The plasma waves were excited with phase velocity $v_{ph} = 81\ V_e$. In actual numbers assuming ambient electron temperatures of the order of .5 eV, the initial secondary flux extends from 4.5 - 18 eV and the waves are created by a flux with a spike at energies larger than 3.2 keV. The waves were allowed to grow up to a certain wave energy level W_1. The ratio of wave energy level over the electron thermal energy W_1/nT_e at which simulations were performed varied between .1 - .5. We will comment on the significance of such values in the next section. The physical basis for a model where the beam waves grow up to a certain level and are subsequently depleted has been described in Papadopoulos [1975] and subsequently confirmed numerically in Palmadesso et al. [1975] and Rowland and Papadopoulos [1977].

The results are shown in Figs. 1-4. In Fig. 1 we show the initial and final electron flux for the three cases under study. As seen from Fig. 2 and from Table I the effect of the collisionless interactions is to change the power law of the secondaries from $E^{-3.2}$ to E^{-1}. The value at which the break occurs depends on the value of W_1/nT_e. The dependence seems to be in accordance with the theory [Papadopoulos 1975, Matthews et al. 1976] which predicts that the velocity v_b at which the break occurs scales with $v_b = \sqrt{6 \frac{nT_e}{W_1}}\ V_e$ (Fig. 3). Unfortunately due to computer limitations we could not perform simulation at much lower values of W_1/nT_e. As will be discussed in the next section, the values of W_1/nT_e used correspond to strong precipitation with number densities of the order of 1 cm^{-3}. Figure 4 shows the energy spectrum of the electron plasma waves as function of the phase velocity at the initial and the final time. It is seen that the waves are parametrically coupled to lower phase velocities where they interact with the ambient particles and modify their distribution function. On the basis of the observed spectrum one can determine the diffusion coefficient in velocity space which will be used in the study which includes both collisional and collisionless effects. Figure 5 shows the spectrum of the low frequency density fluctuations. From this spectrum one can compute the anomalous resistivity as discussed in Papadopoulos and Coffey [1974b].

IV. Conclusions and Discussion

On the basis of the above results we can answer the questions set forth in the introduction. It has been shown that the existence of plasma waves even in a region where they are non-resonant with the ambient particles can significantly modify the observed flux power law. It was also shown that while the index of the power law is independent of the initial wave energy density, the velocity at which the break occurs is consistent with the relationship $\frac{V_b}{V_e} \approx \sqrt{6 \frac{nT_e}{W_1}}$.

Finally large density fluctuations were created by the ponderomotive force of the high frequency waves. Such waves can produce anomalous resistivity as discussed in Papadopoulos and Coffey [1974] and Rowland et al. [1977].

Applicability of the Model to the Aurora Zone

While the model as discussed above and therefore its conclusions, is completely self consistent, its applicability to the auroral zones requires some further discussion. What we have demonstrated here is that given an initial secondary spectrum $E^{-3.2}$, such as expected from collisional interactions and a wave energy level $\frac{W_1}{nT_e} \approx .1 - .5$, one can account for the observations. Electron plasma waves have been detected in the auroral zones with energy densities comparable to the above [Spiger et al 1975]. In addition observation of the primary electron spectrum indicates that such waves must be generated in accordance with plasma theory [Papadopoulos and Coffey 1974a; Matthews et al 1976]. As discussed in the previous papers if

$$\frac{n_b}{n} > 36 \left(\frac{T_e}{\epsilon_b}\right)^3 \frac{\Delta v}{V_o} \tag{1}$$

where ϵ_b the energy of the precipitating particles and V_o, ΔV their velocity and velocity spread the value of $\frac{W_1}{nT_e}$ will be given by

$$\frac{W_1}{nT_e} \approx 10^5 A \left(\frac{n_b}{n}\right)^2 \left(\frac{V_o}{\Delta V}\right)^4 \qquad (2)$$

where A is the atomic number of the dominant ionic species. Inequality (1) is easily satisfied in the auroral zones. It is important to notice that in Eq. (2) $\frac{W_1}{nT_e}$ does not depend on the energy of the precipitating particles but only on the relative energy spread which observations indicate is relatively constant. Taking $A \approx 16$, $n \approx 10^5 cm^{-3}$ and $\frac{V_o}{\Delta V} \approx 5$ as rather constant conditions, it turns out that $\frac{W_1}{nT_e} \approx 10^{-1} n_b{}^2$. The value of n_b is the only one that can vary significantly. For strong auroras $n_b \approx 1$ and the values used in our simulations are appropriate. For weaker auroras $n_b \sim 10^{-1}$ and much smaller values of should be used. Unfortunately the simulations for such values become increasingly lengthy and we could not carry them out. However we expect the basic results to be valid since even for such weak fields the conditions for parametric coupling to secondary waves are easily satisfied.

In conclusion we can state that the particle simulations confirm the fact that collisionless interactions can be responsible for the break from E^{-3} dependence of the secondary electrons. The velocity at which the break occurs is given by $\frac{v_b}{V_e} \approx \sqrt{6 \frac{nT_e}{W_1}}$. For the above parameters we find the scaling law $\frac{v_b}{V_e} \alpha\, n_b{}^{-1}$, while the E^{-1} dependence in essentially independent of the value of n_b. Finally it was shown that resistivity can be enhanced due to the density fluctuation with $\left(\frac{\delta n}{n}\right)^2 \approx 10^{-3}$ at $k\lambda_D \approx .1$. A more extensive treatment of this subject will appear elsewhere.

Acknowledgment

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Table I

$\frac{W_1}{nT_e}$	α	V_b	$\frac{W_2}{nT_e}$	$10^{-3}\left(\frac{\delta n}{n}\right)^2$
.13	$1 \pm .5$	$6.46 \pm .2$	.08	1
.24	$1 \pm .5$	$5.7 \pm .2$	.05	2
.44	$.9 \pm .2$	$3.5 \pm .3$	.05	3

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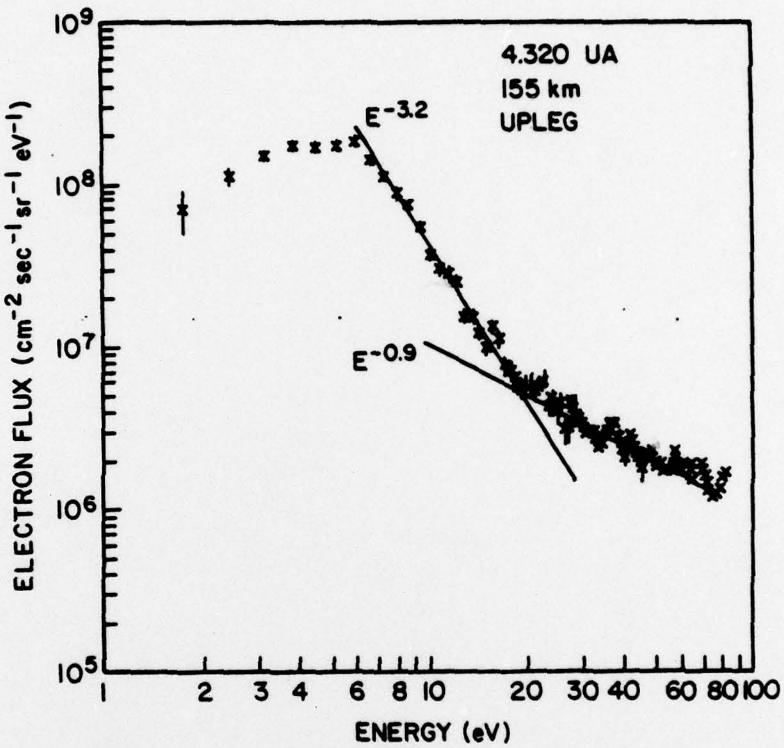


Fig. 1 — Secondary electron spectrum observed by Feldman and Doering

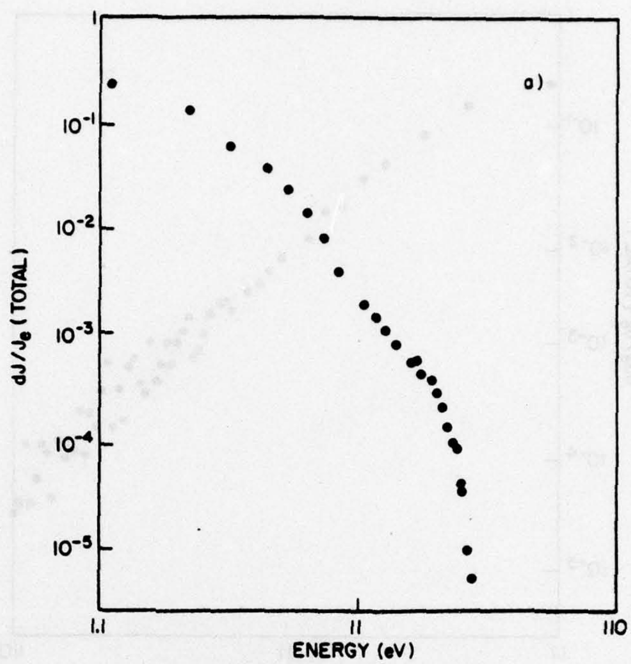


Fig. 2 — (a) Initial electron flux

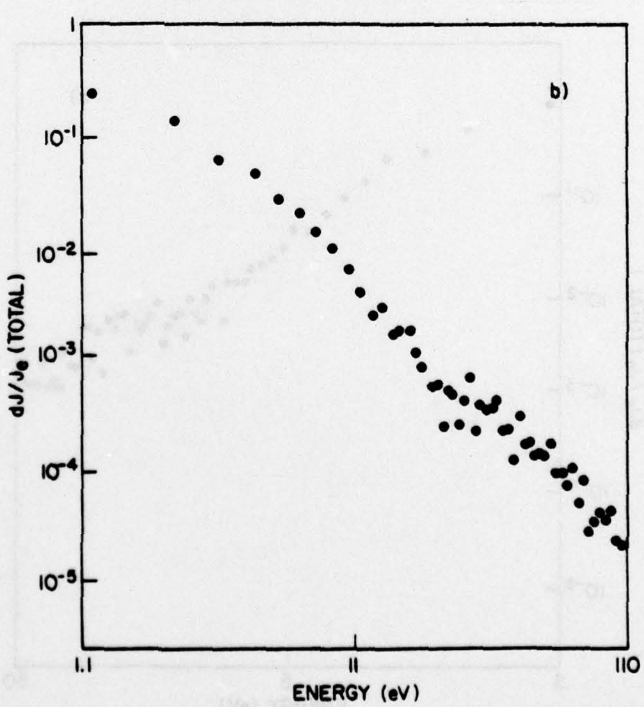


Fig. 2 — (b) Final electron flux W_1 = .13

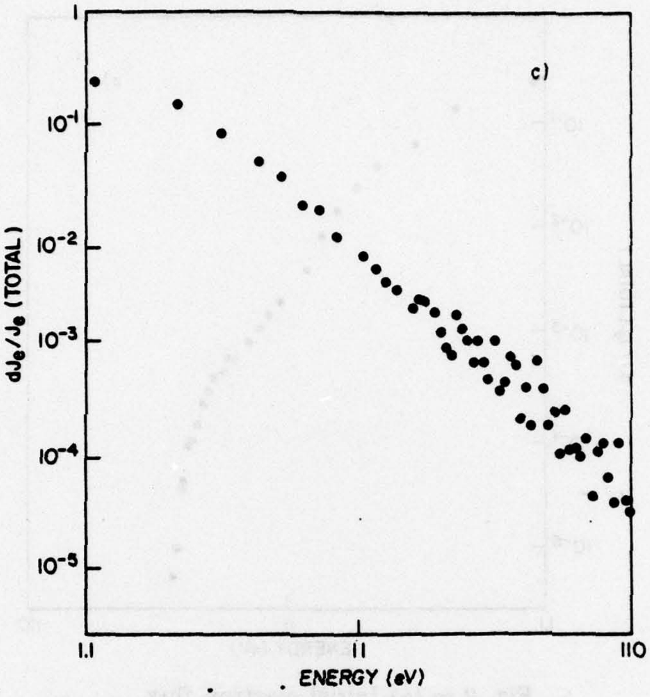


Fig. 2 — (c) Final electron flux W_1 = .24

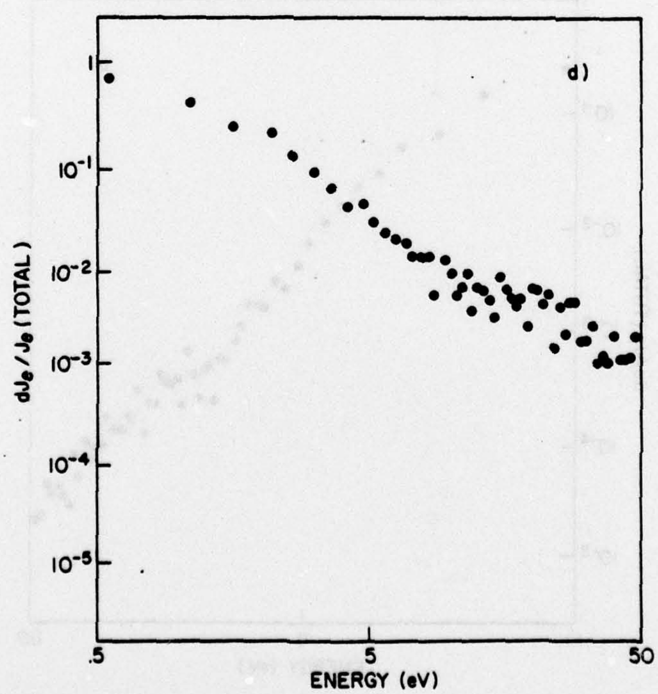


Fig. 2 — (d) Final electron flux W_1 = .44
(Note change of scale)

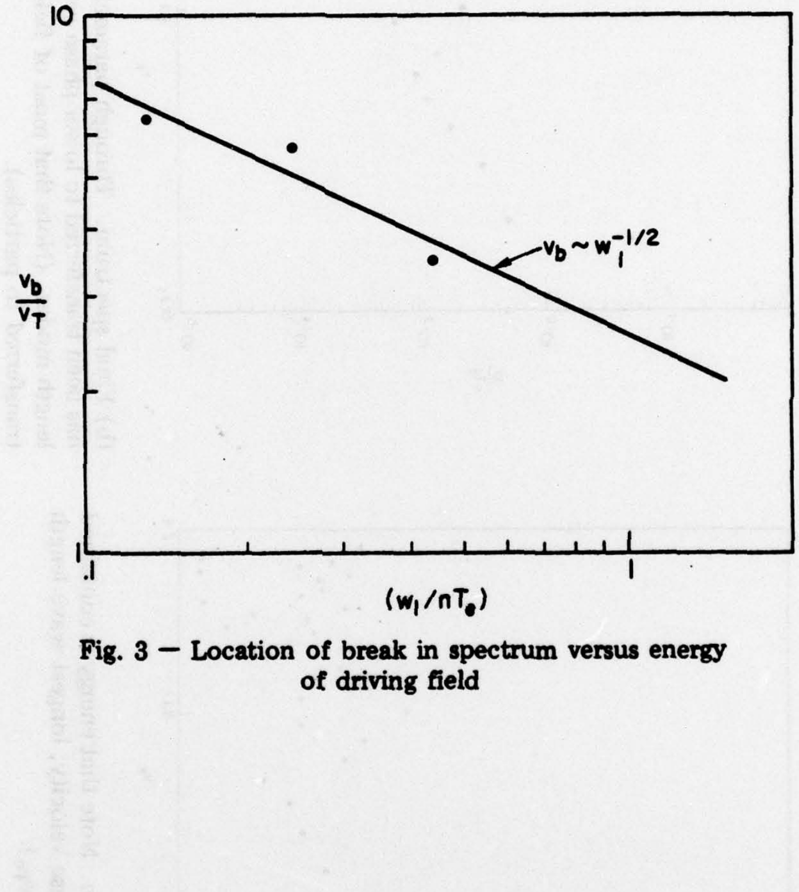
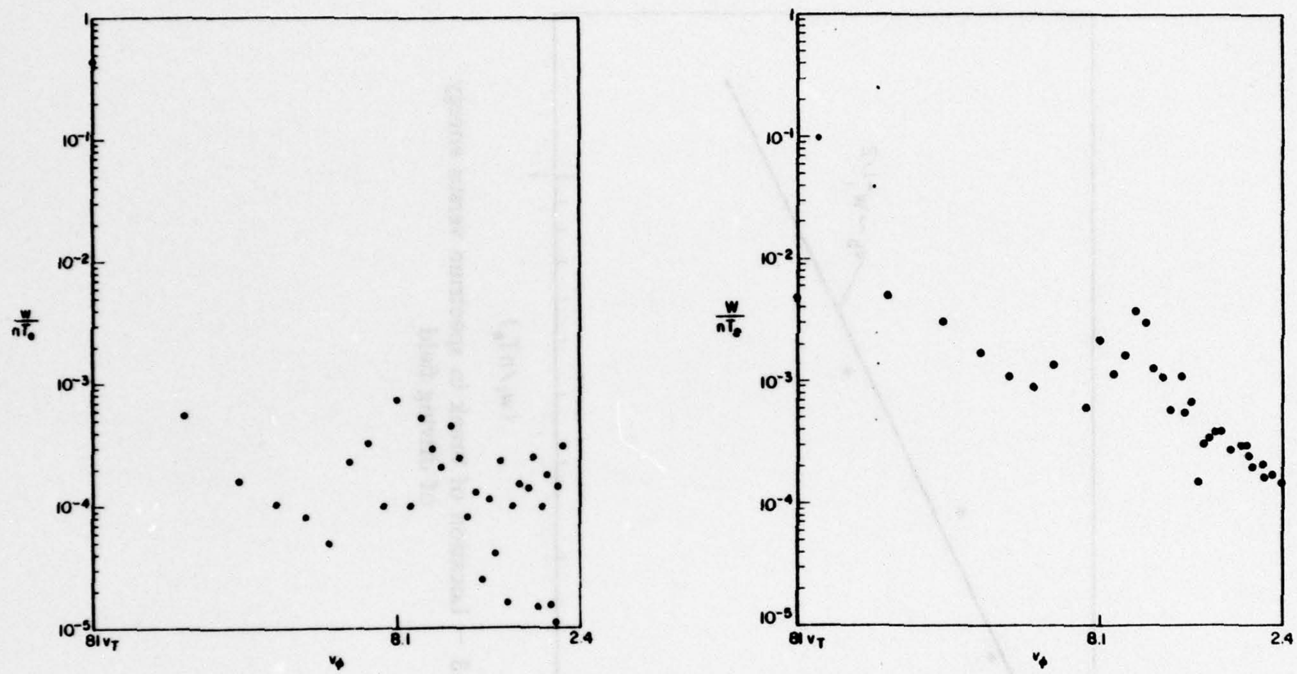


Fig. 3 — Location of break in spectrum versus energy of driving field



(a) Initial spectrum. Note that energy is contained in the highest phase velocity, longest wave length modes ($\nu_{ph} = 81\ v_{Te}$).

(b) Final spectrum. Through parametric effects energy has been transferred to lower phase velocity short wavelength modes. (Note that most of field energy has been transferred to particles).

Fig. 4 — Electric field energy spectrum as function of phase velocity $W_1 = .44$

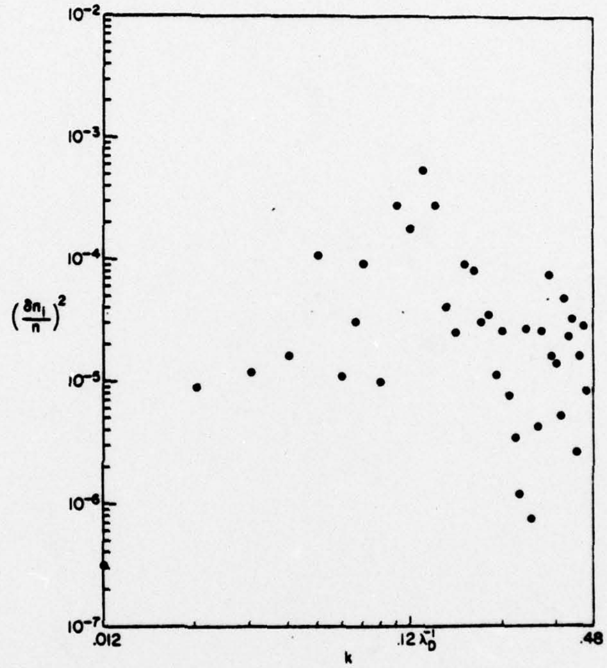


Fig. 5 — Ion density fluctuations W_1 = .44